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(54) **MIGRATING TASKS BETWEEN ASYMMETRIC COMPUTING ELEMENTS OF A MULTI-CORE PROCESSOR**

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(75) Inventors: **Alon Naveh**, Ramat Hasharon (IL); **Yuval Yosef**, Hadera (IL); **Eliezer Weissmann**, Haifa (IL); **Anil Aggarwal**, Portland, OR (US); **Efraim Rotem**, Haifa (IL); **Avi Mendelson**, Haifa (IL); **Ronny Ronen**, Haifa (IL); **Boris Ginzburg**, Haifa (IL); **Michael Mishaeli**, Zichron Yaakov (IL); **Scott D. Hahn**, Hillsboro, OR (US); **David A. Koufaty**, Portland, OR (US); **Ganapati Srinivasa**, Portland, OR (US); **Guy Therien**, Beaverton, OR (US)

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*Primary Examiner* — Benjamin P Geib  
*Assistant Examiner* — William V Nguyen

(74) *Attorney, Agent, or Firm* — Trop, Pruner & Hu, P.C.

(57) **ABSTRACT**

In one embodiment, the present invention includes a multicore processor having first and second cores to independently execute instructions, the first core visible to an operating system (OS) and the second core transparent to the OS and heterogeneous from the first core. A task controller, which may be included in or coupled to the multicore processor, can cause dynamic migration of a first process scheduled by the OS to the first core to the second core transparently to the OS. Other embodiments are described and claimed.

**19 Claims, 10 Drawing Sheets**

(73) Assignee: **Intel Corporation**, Santa Clara, CA (US)

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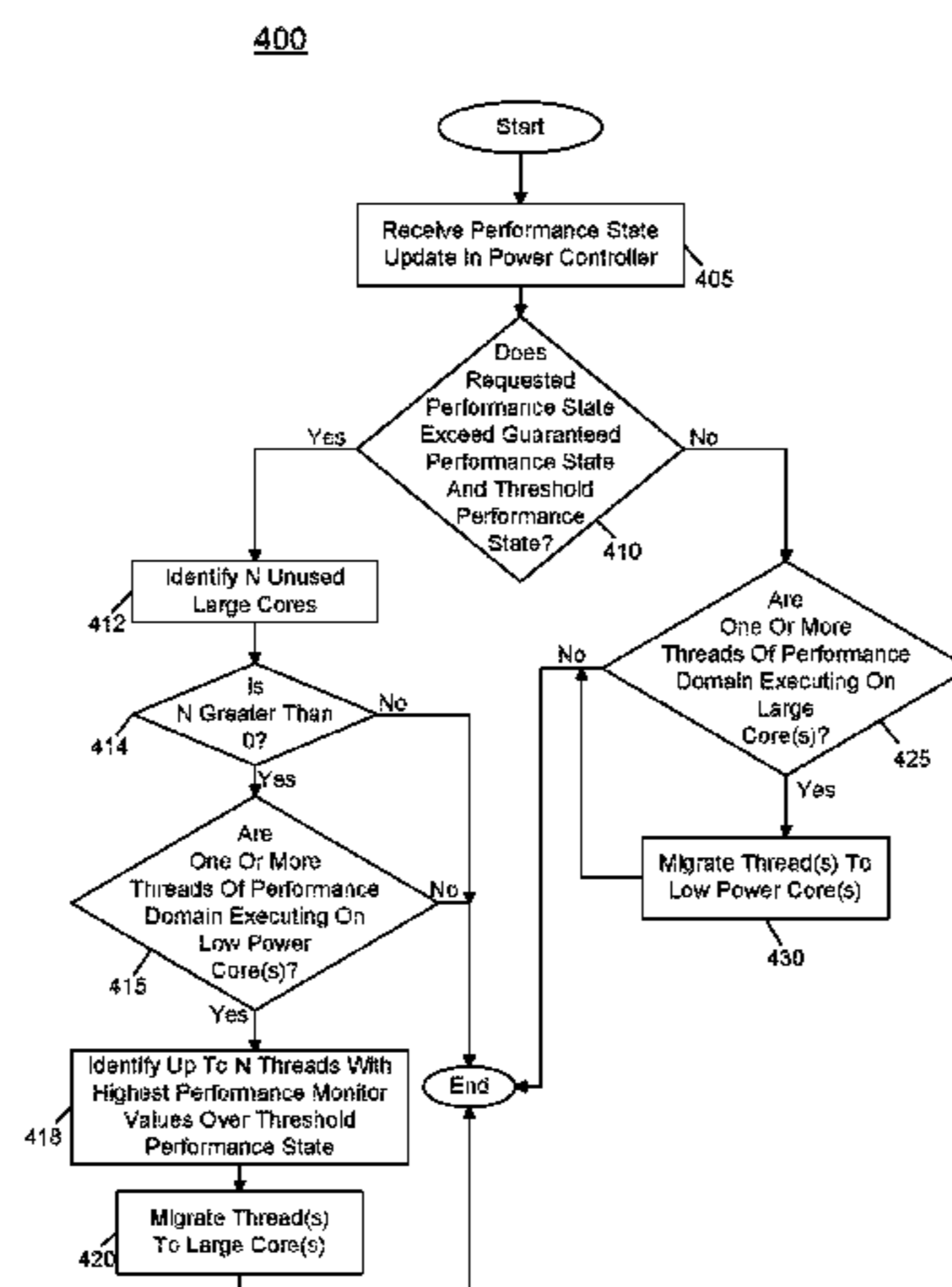
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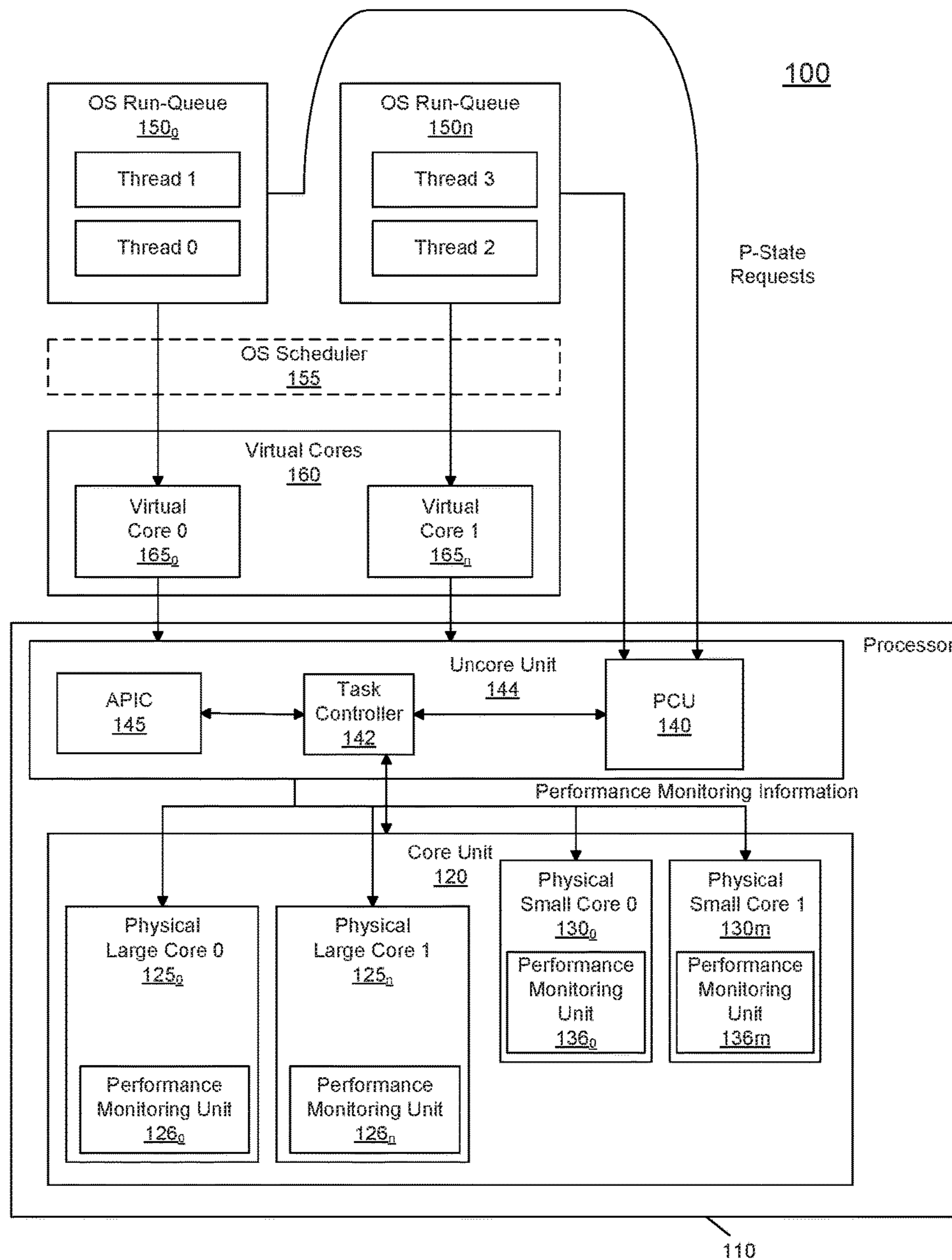


FIG. 1

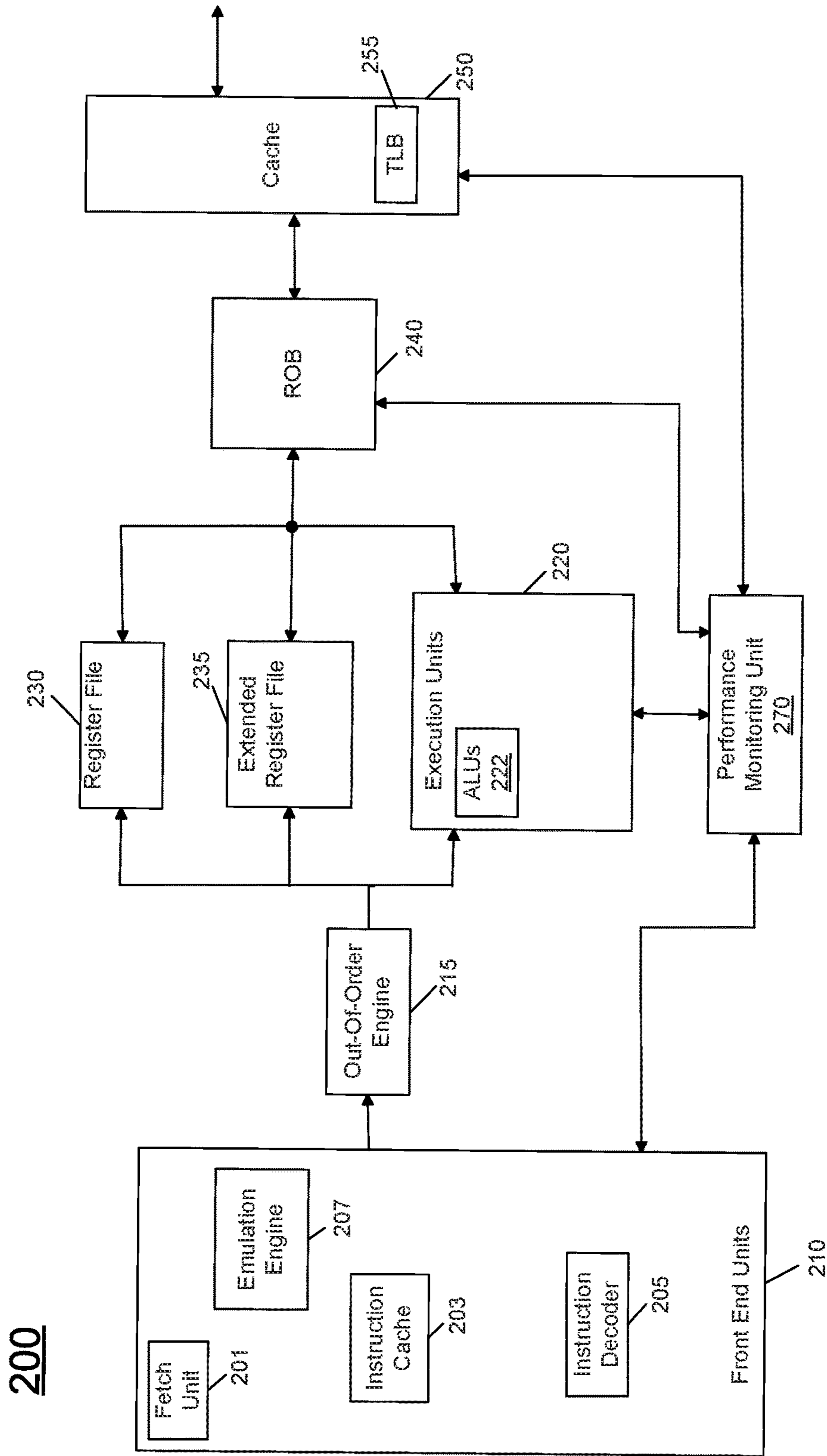


FIG. 2

300

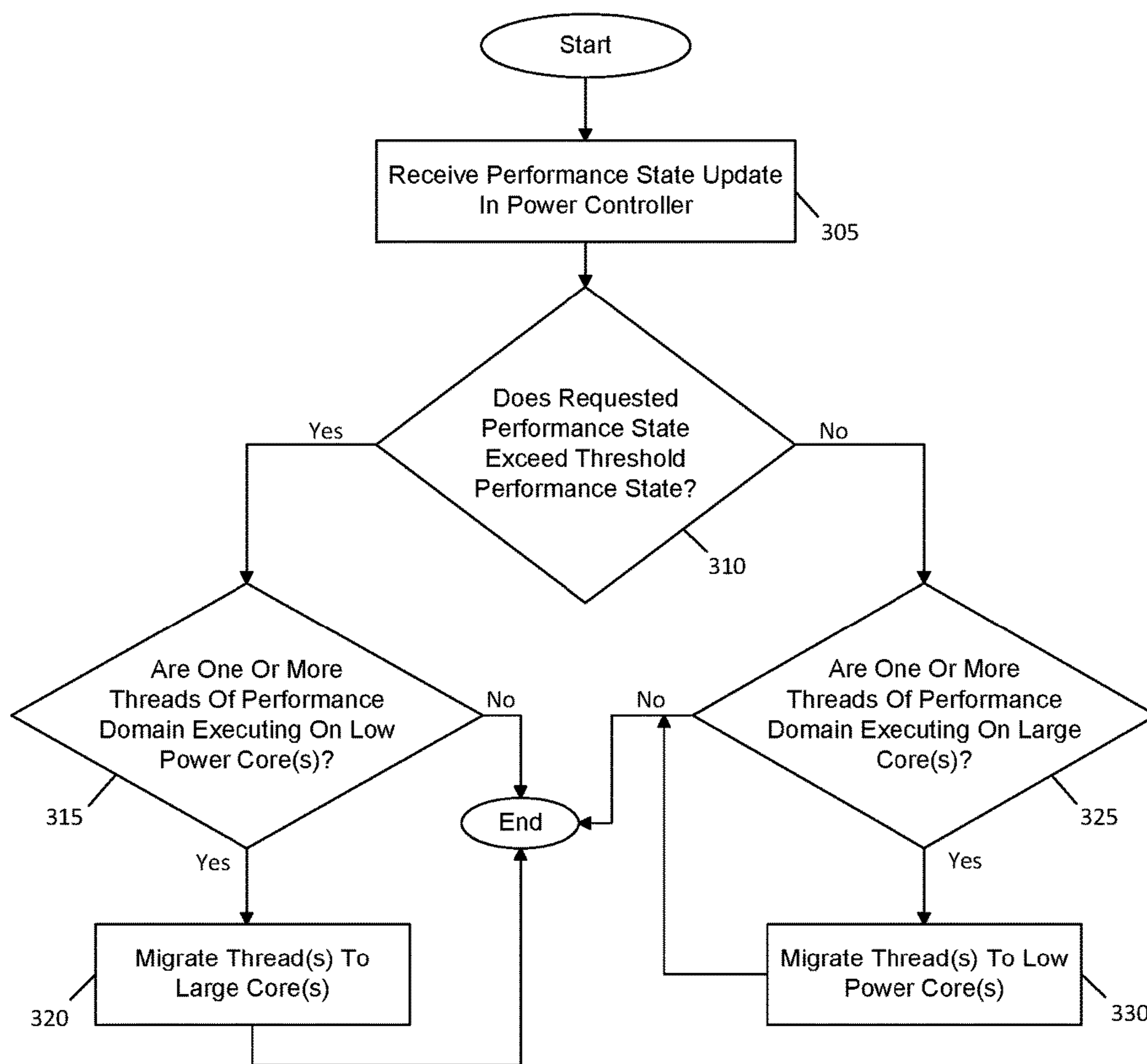


FIG. 3

350

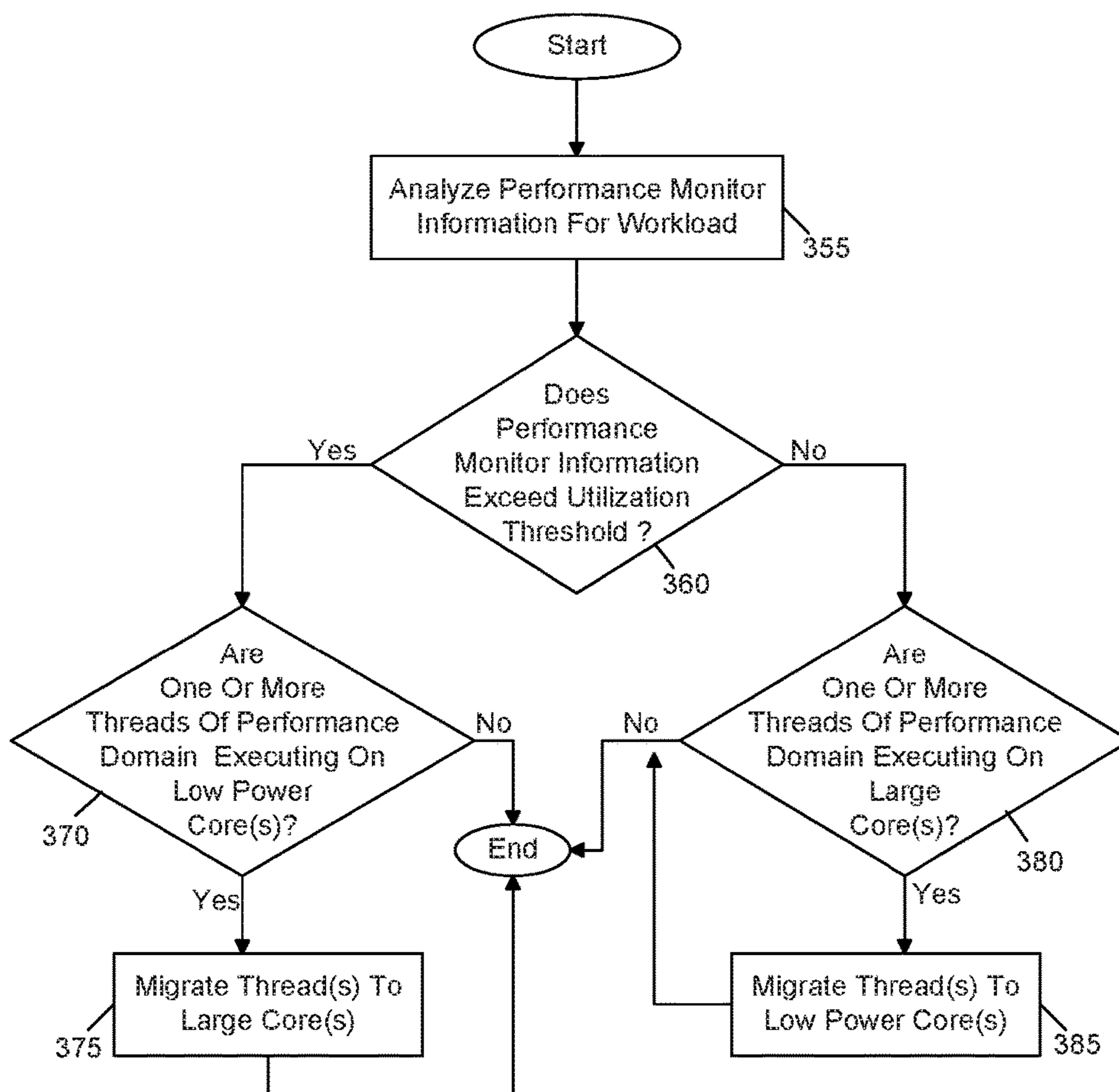


FIG. 4

400

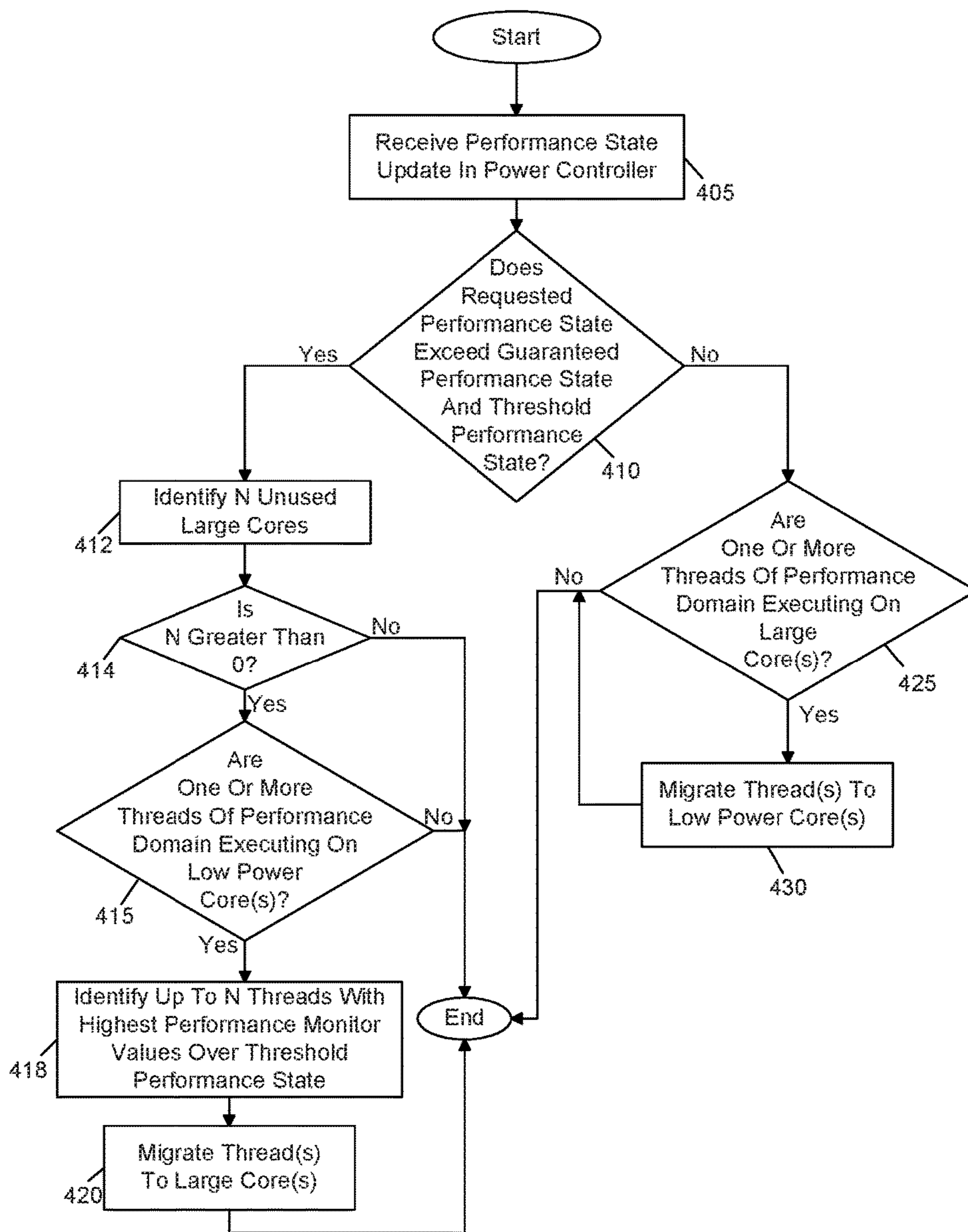


FIG. 5



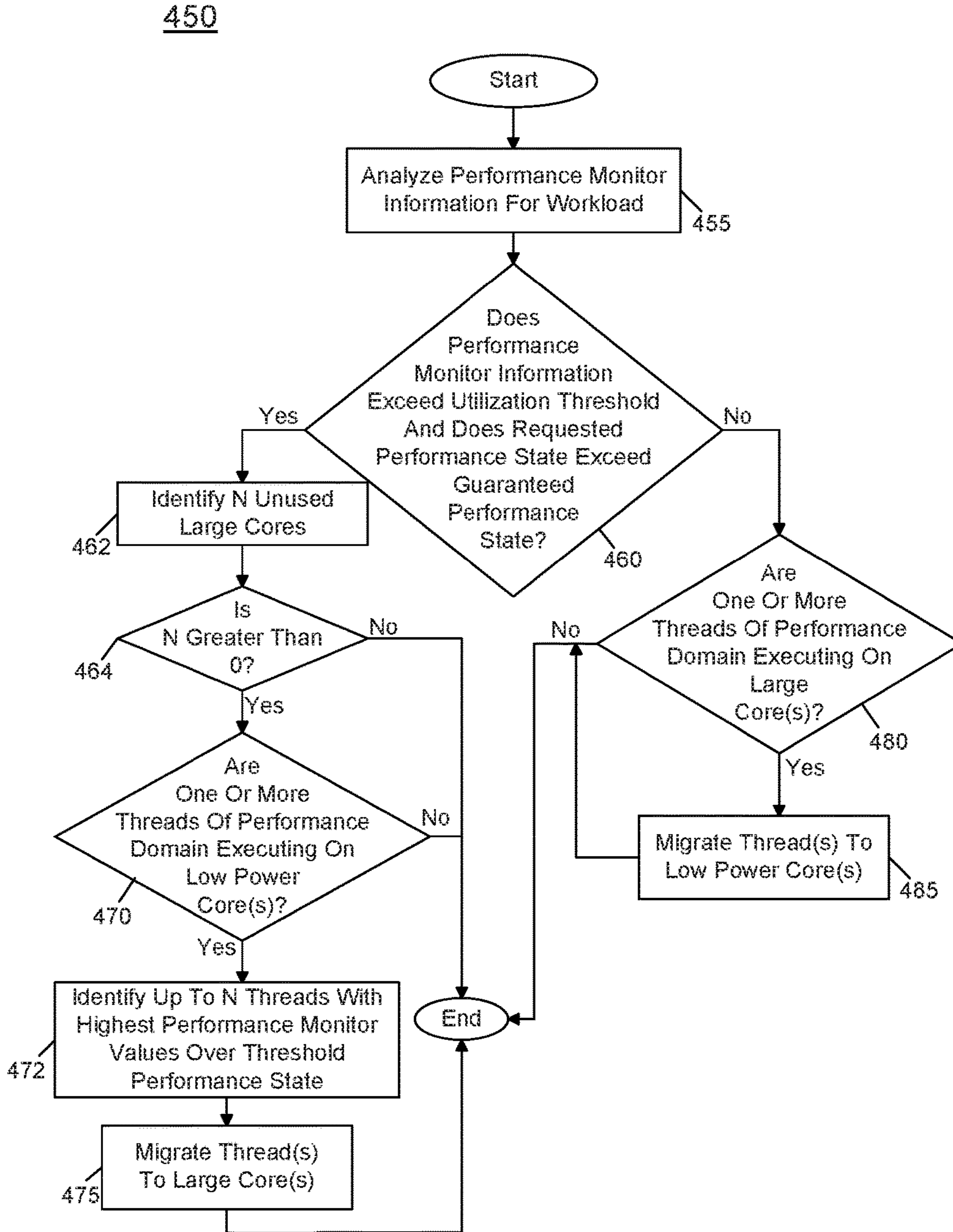


FIG. 6

600

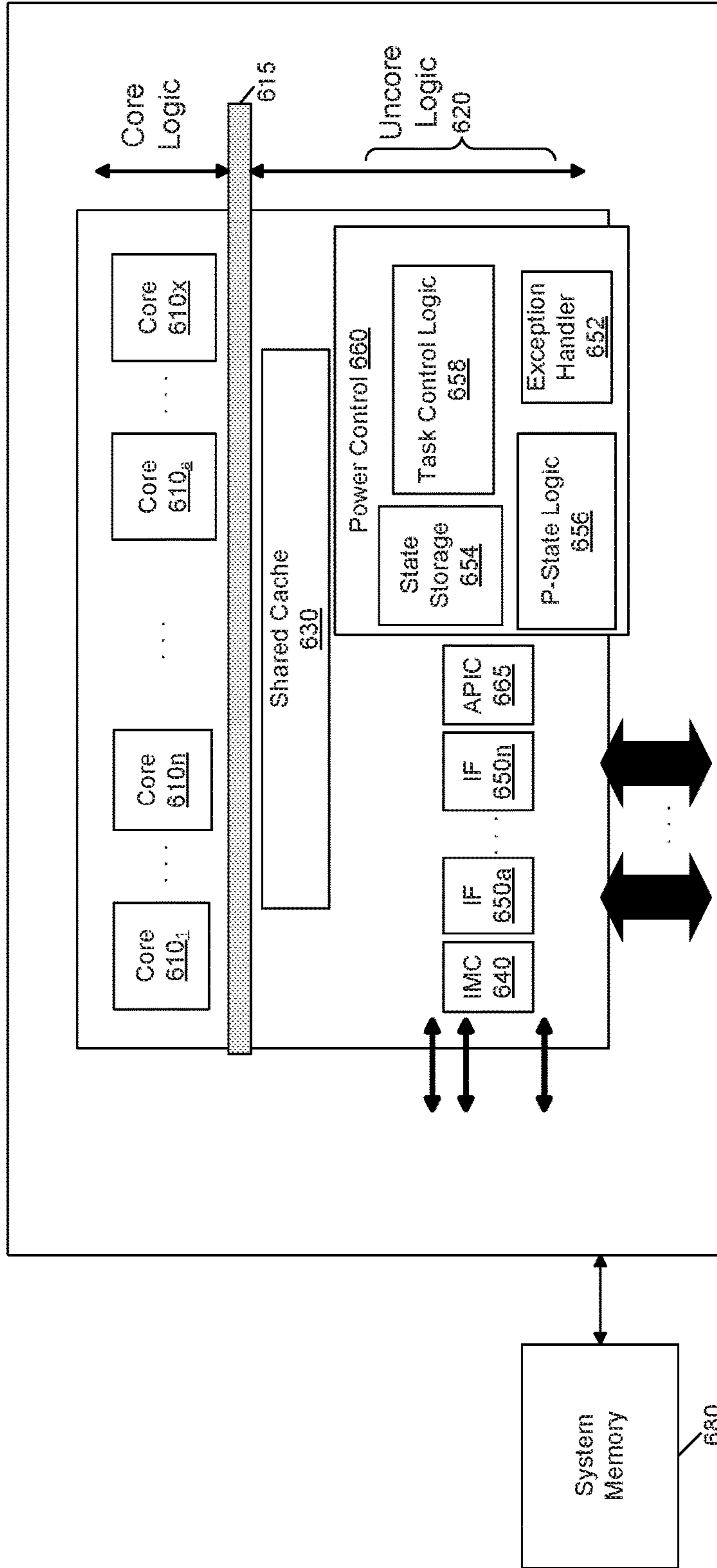


FIG. 7

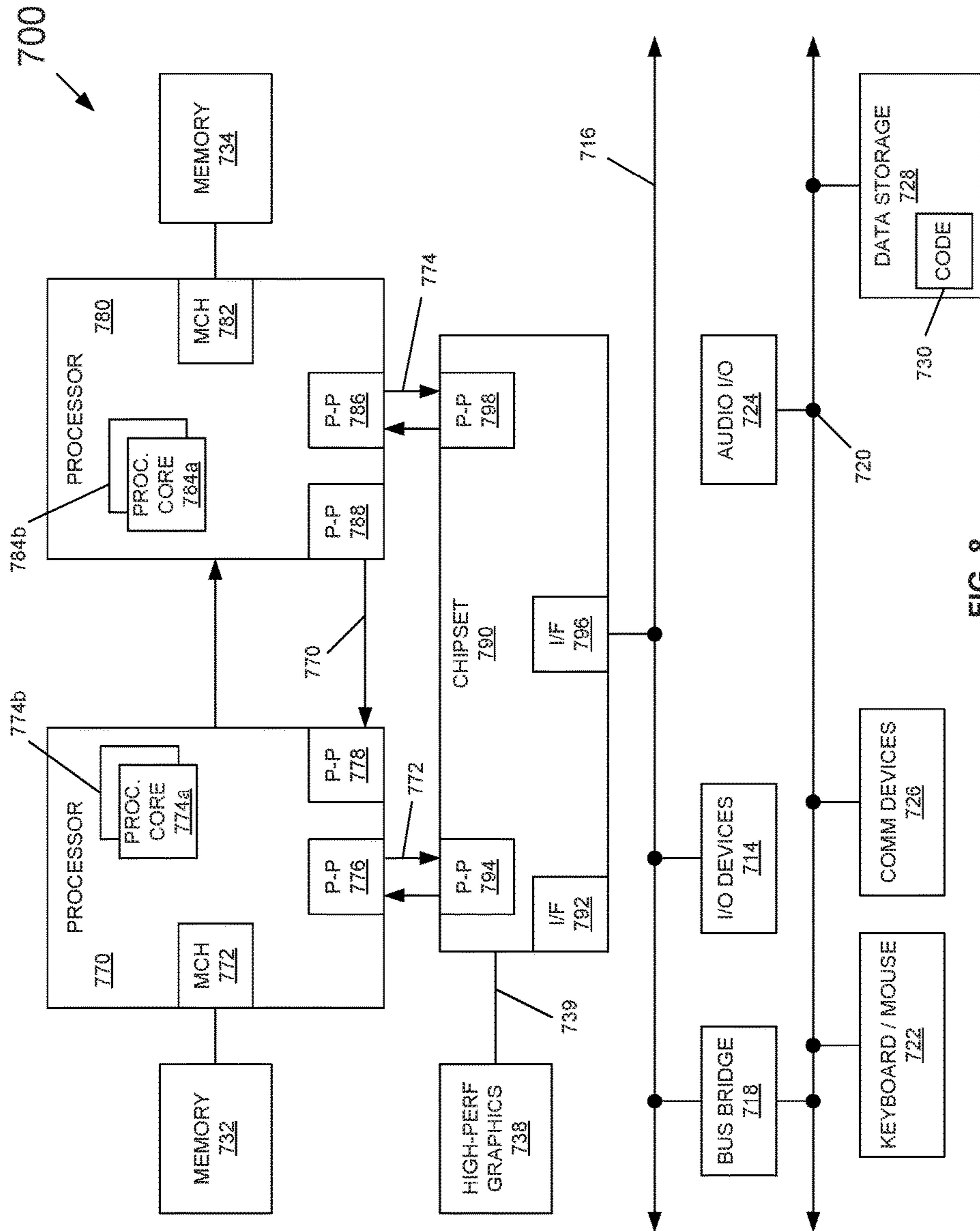


FIG. 8

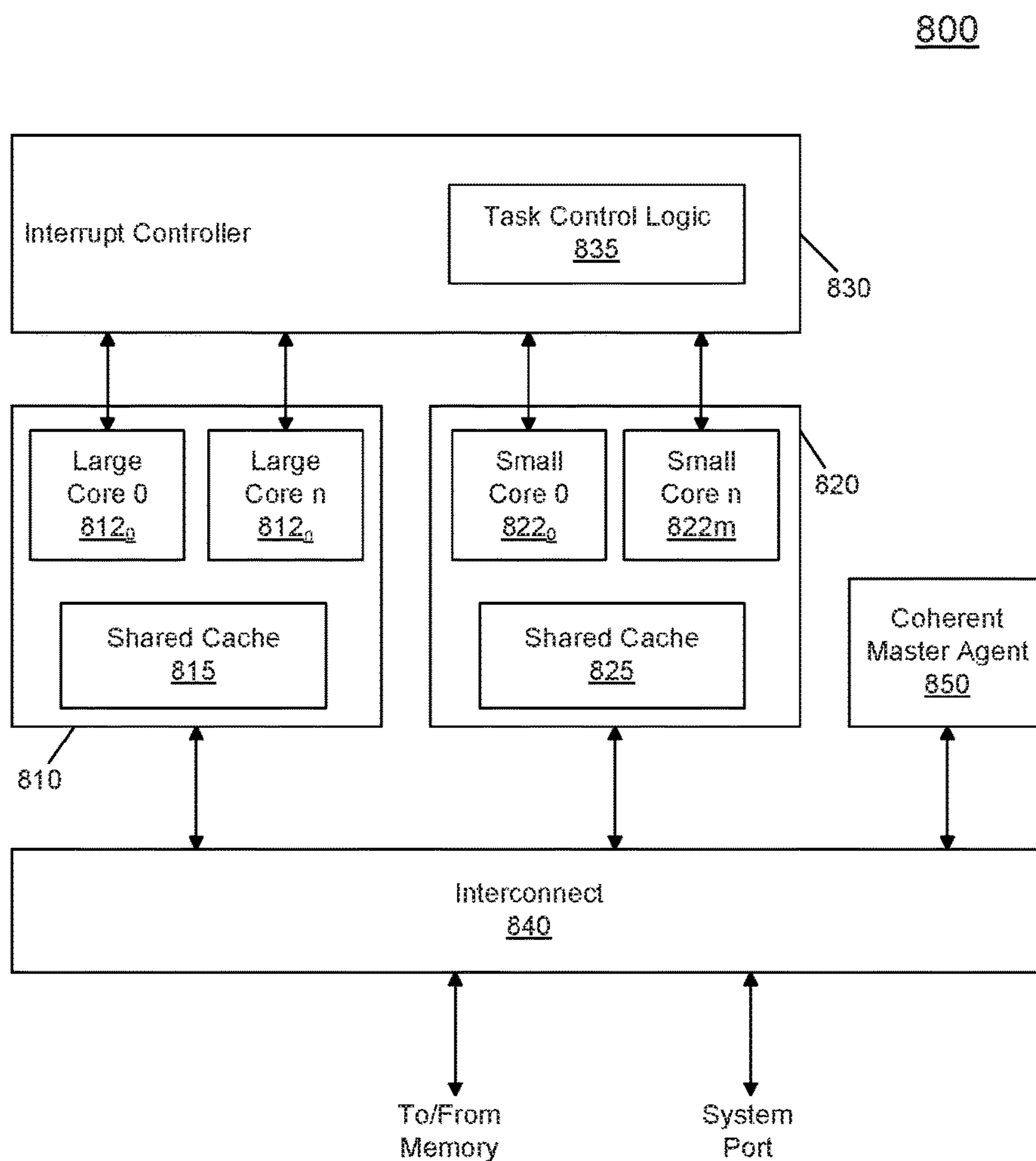


FIG. 9

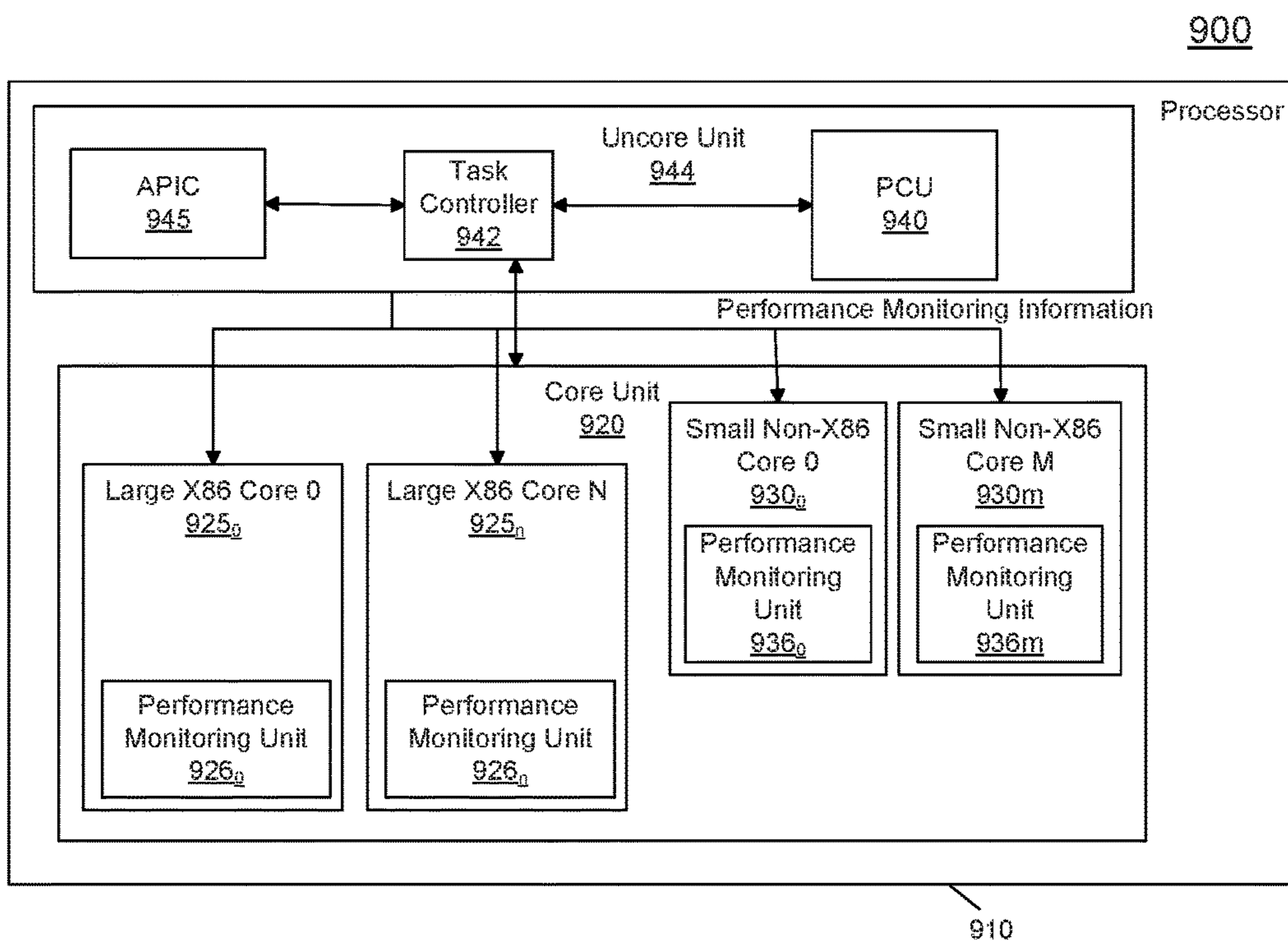


FIG. 10

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## MIGRATING TASKS BETWEEN ASYMMETRIC COMPUTING ELEMENTS OF A MULTI-CORE PROCESSOR

### TECHNICAL FIELD

Embodiments relate to migration of tasks in a multicore processor.

### BACKGROUND

Modern processors are often implemented with multiple cores. Typically, all of these cores are of a homogenous nature. That is, each core is of an identical design and thus has an identical layout, implements the same instruction set architecture (ISA), and so forth. In turn, an operating system (OS) of a system including the processor can select any of these multiple cores to handle tasks.

As time progresses, processors are being introduced with heterogeneous resources. Oftentimes these resources are specialized accelerators to perform specialized tasks. However, it is anticipated that processors will be introduced that include heterogeneous cores that have different characteristics. An OS that is designed for a symmetric system cannot be used with such a processor without additional hardware or software support to hide differences between the cores.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a system arrangement in accordance with an embodiment of the present invention.

FIG. 2 is a block diagram of a processor core in accordance with one embodiment of the present invention.

FIG. 3 is a flow diagram of a method for dynamically migrating threads in accordance with an embodiment of the present invention.

FIG. 4 is a flow diagram a method for dynamically migrating threads in accordance with another embodiment of the present invention.

FIG. 5 is a flow diagram of a method for dynamically migrating threads between cores in accordance with a still further embodiment of the present invention.

FIG. 6 is a flow diagram of a method for dynamically migrating threads between cores in accordance with yet another embodiment of the present invention.

FIG. 7 is a block diagram of a processor in accordance with another embodiment of the present invention.

FIG. 8 is a block diagram of a system in accordance with an embodiment of the present invention.

FIG. 9 is a block diagram of a processor in accordance with another embodiment of the present invention.

FIG. 10 is a block diagram of a processor in accordance with another embodiment of the present invention.

### DETAILED DESCRIPTION

In various embodiments a multicore processor can include heterogeneous resources including cores having heterogeneous capabilities, for example, with the same instruction set architectures (ISAs) but having differing performance capabilities or even different ISAs. Furthermore, the heterogeneous nature of these resources can be maintained transparently to an operating system (OS). To this end, embodiments provide a mechanism that can be implemented in a very lightweight manner, leveraging information and logic present in a given processor to control allocation of tasks to the different resources transparently to the OS. In this way,

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embodiments can take advantage of the features of the different resource types to efficiently perform instructions with reduced power consumption and improved execution speeds. Embodiments are directed to processor architectures and hardware support that provide for resources to be used transparently to an operating system, and thus avoid the need to enable a heterogeneous processor or other resource to be supported by the operating system or hypervisor.

By integrating cores with different performance capabilities such as large cores having high single thread performance and small cores having higher power efficiency, overall power efficiency of a processor can be increased without sacrificing performance. This processor can be an asymmetric multiprocessor, namely an OS-transparent asymmetric multiprocessor (AMP) system, details of which are described below. In various embodiments having such a heterogeneous architecture, control between the cores can be realized without OS support in a system in which the OS assumes that all cores are equal. Embodiments may further enable fast, transparent (to OS) switch of code execution between the different types of cores.

In various embodiments, only a single core type can be exposed to the OS, which may be a legacy OS, with one or more other core types present in the processor remaining completely hidden from the OS. Although described as cores, understand that in various embodiments other processing engines such as fixed function units, graphics units, physics units and so forth may also be transparent to the OS. For purposes of discussion, assume that the large core type is exposed to the OS. Accordingly, the OS schedules processes to one or more of these large cores. The re-assignment of processes to the transparent cores, and related to it process migration between cores, can be done leveraging information readily available in the processor, such as performance state information and/or performance monitoring information received in a task controller of the processor, also referred to herein as a task control unit. Note that as used herein, a process migration may generally refer to migration of an execution context between cores or other resources.

In one embodiment, this task controller may be a separate logic or unit of the processor, and can be used to migrate processes between cores transparently to the OS. In other embodiments, this task controller may be combined and incorporated with a power control unit or other power controller of the processor. However, these units may logically be different in that the task controller receives inputs from the power control unit, performance counters, and so forth, and makes a decision on thread migration. As such, the task controller acts more like a micro-scheduler than a power controller. In various embodiments, the task controller can cause assignment of tasks to physical cores, thus maintaining transparency of the actual hardware structure with respect to the OS. In some embodiments, the task controller can be configured to communicate with an advanced programmable interrupt controller (APIC) of the processor to thus provide virtualization between a virtual core to which the OS allocates a task and a physical core on which the task is actually executing. To this end, in some embodiments the APIC can receive process allocations from the OS which include a core identifier (which in some embodiments can be in the form of an APIC ID) and initially assign the task using an APIC ID-to-core ID mapping table to a core visible to the OS, e.g., a large core. Then, the task controller can cause a migration of this process to a core that is not visible to the OS, e.g., a small core and reflect the switch by interfacing with the APIC to update the mapping table of the APIC. Thus the task controller may replace

under the hood the physical core that the OS controls. As part of this replacement, the task controller can update the APIC mapping in order to hide from the OS the fact that the physical cores were replaced.

Although the scope of the present invention is not limited in this regard, in some embodiments the task controller can cause a process migration between cores mainly based on following factors: operating system performance requests, performance monitoring information, and availability of physical resources like power and thermal. Note that the task controller can stop a process execution on one core and migrate it to another physically different core at any time during a process life.

Referring now to FIG. 1, shown is a block diagram of a system arrangement in accordance with an embodiment of the present invention. As shown in FIG. 1, system 100 includes a processor 110 which can be a multicore processor that includes a core unit 120 having heterogeneous resources such as cores physically disparate in size and available resources. Specifically in the embodiment of FIG. 1, different types of hardware or physical cores can be present, including a plurality of so-called large cores 125<sub>0</sub>-125<sub>n</sub> (generically large core 125), and a plurality of so-called small cores 130<sub>0</sub>-130<sub>m</sub>, (generically small core 130) (note that different numbers of large and small cores may be present). In many embodiments, these different core types can be of the same ISA but having performance differences such as by way of different micro-architectures such as a larger, out-of-order core type and a smaller, in-order core type.

Note however that in still other embodiments, the heterogeneous cores can be of different ISAs such as a given instruction set architecture and a subset of this instruction set architecture. For example, large cores 125 can execute all instructions of an ISA, while small cores 130, which may have a lesser number of architectural and micro-architectural resources including different/smaller register structures, execution units and so forth, can only execute a subset of the ISA. In this way, the different ISAs can partially overlap. In other embodiments, the ISAs to be handled by the different core types can be completely different. In cases where the ISAs are different, non-supported instructions can be executed on a core by an emulation engine, or can instead be handled by issuing a fault which can cause a migration back to a supporting core.

As further seen in FIG. 1, processor 110 further includes an uncore unit 144 with various components, representative ones of which are shown in FIG. 1. As seen, uncore unit 144 includes a power controller 140, also referred to herein as a power control unit (PCU). In various embodiments PCU 140 may be a hardware-based logic that can perform power management and control for the processor. Processor 110 can operate in one of multiple performance states. In one embodiment, an OS can issue a request to change a performance state or so-called P-state of a core via a request to a PCU 140. In turn responsive to this request, the PCU can communicate a performance state with a task controller or task control unit (TCU) 142. Along with additional information such as performance monitoring information from the cores, TCU 142 can trigger an asynchronous interrupt to enable an OS transparent migration between different core types. Similar migrations can occur due in part to performance state information received in TCU 142 from PCU 140.

Note that the performance states can be according to an OS-based mechanism, namely the Advanced Configuration and Platform Interface (ACPI) standard (e.g., Rev. 3.0b,

published Oct. 10, 2006). According to ACPI, a processor can operate at various power and performance states or levels. With regard to power states, ACPI specifies different power consumption states, generally referred to as so-called C1 to Cn states. When a core is active, it runs at a so-called C0 state, and when the core is idle it may be placed in a core low power state, a so-called core non-zero C-state (e.g., C1-C6 states). In addition to these power states, a processor can further be configured to operate at one of multiple performance states, namely from P0 to PN. In general, the P1 performance state may correspond to the highest guaranteed performance state that can be requested by an OS. In general the different P-states correspond to different operating frequencies at which a core can run.

Note that the P-state control can be more finely controlled than on a processor-wide basis. In different embodiments, each core (or even portion of the core) can operate at independent performance levels and accordingly, one or more cores or portions thereof can be considered to be an independent performance domain.

Increasing the performance or efficiency of code execution can be defined by minimizing the amount of time that it takes to complete a defined amount of work. Increasing the performance efficiency mostly causes consumption of more power, while saving power typically has a negative effect on the performance efficiency.

Increasing the power/performance efficiency of code execution can be defined by minimizing the ratio between the energy that is consumed to complete a defined amount of work and the execution time that it takes to execute this work. For example saving power but still executing the same amount of work or minimizing the time to execute the same amount of work without increasing the power consumption increases the power/performance efficiency. Embodiments may be used to increase the power/performance efficiency.

FIG. 1 also shows the presence of APIC 145 that may receive various incoming interrupts, both from the OS as well as hardware-based interrupts and map such interrupts to a requested core. Furthermore, in accordance with an embodiment of the present invention, dynamic remapping can occur based on control from TCU 142 such that the TCU can dynamically migrate threads between the asymmetric cores transparently to the OS. Note that in some implementations may provide a distributed APIC architecture such that an APIC may be present in each core, with a central APIC unit present, e.g., in the PCU/TCU.

As further shown in FIG. 1, the OS may further provide P-state requests directly to PCU 140, which can provide such information to TCU 142 to perform dynamic migrations in accordance with an embodiment of the present invention. As further seen, TCU 142 may also receive incoming performance monitoring information from corresponding performance monitoring units 126<sub>0</sub>-126<sub>n</sub> and 136<sub>0</sub>-136<sub>m</sub> of the cores.

Incoming thread allocations from the OS are made to a given virtual core that can either be a large or small core depending upon the implementation. In general, only one type of core is visible to the OS. Note that switching of processes between the different cores can be done much faster (and at higher frequencies) than an OS context switch. For example, an OS-triggered context switch can occur approximately one per millisecond (ms), while hardware-triggered context switches can occur within several tens of microseconds ( $\mu$ s).

As further seen in FIG. 1, a software view of system 100 is also provided. Specifically, system 100 can execute an OS that is designed for a symmetric processor and can be used

with processor 110 although the processor is of an asymmetric design. This asymmetry can be hidden from the OS via task controller 142 using mechanisms as described herein by enabling the OS to control only a single core type, and by making only single types of cores visible for the OS control.

As seen, the software portion of system 100 can include multiple OS run queues 150<sub>o</sub>-150<sub>n</sub> (generically run queues 150). Each queue can include multiple threads, e.g., scheduled by an OS scheduler 155. As seen, OS scheduler 155 has a view of the hardware of processor 110 as having virtual cores 160 that include virtual large cores 165<sub>o</sub>-165<sub>n</sub>, e.g., corresponding to large cores 125<sub>o</sub>-125<sub>n</sub>. That is, the small cores remain transparent to the OS. Note that in other implementations, the OS may have a virtual view of the small cores and the large cores can remain transparent to the OS. In general, the OS will enumerate only a single type of core. Without loss of generality the examples described herein assume two different die size of core type, with or without the same ISA support. Embodiments may also include a processor including two or more types of cores, while the difference between the cores may not necessarily be the die size of the cores or the group of ISA that each core supports.

Using the arrangement in FIG. 1, the software provides threads to be executed within processor 110. More specifically, via OS scheduler 155 threads, e.g., 0 and 1 of OS run queue 150<sub>o</sub>, can be scheduled to virtual core 165<sub>o</sub>, which the OS associates with large core 125<sub>o</sub> and the threads 2 and 3 of run queue 150<sub>n</sub> can be scheduled to virtual core 165<sub>n</sub>, which the OS associates with large core 125<sub>n</sub>. Although shown with this particular implementation in the embodiment of FIG. 1, understand the scope of the present invention is not limited in this regard.

Embodiments can be implemented in many different processor types. For example, embodiments can be realized in a processor such as a multicore processor. Referring now to FIG. 2, shown is a block diagram of a processor core in accordance with one embodiment of the present invention. As shown in FIG. 2, processor core 200 may be a multi-stage pipelined out-of-order processor. Processor core 200 is shown with a relatively simplified view in FIG. 2 to illustrate various features used in connection with dynamic hardware context switching in accordance with an embodiment of the present invention.

As shown in FIG. 2, core 200 includes front end units 210, which may be used to fetch instructions to be executed and prepare them for use later in the processor. For example, front end units 210 may include a fetch unit 201, an instruction cache 203, and an instruction decoder 205. In some implementations, front end units 210 may further include a trace cache, along with microcode storage as well as a micro-operation storage. Fetch unit 201 may fetch macro-instructions, e.g., from memory or instruction cache 203, and feed them to instruction decoder 205 to decode them into primitives such as micro-operations for execution by the processor. Front end units 210 may further include an emulation engine 207 that can receive incoming instructions that are not supported by the underlying ISA of the core and emulate them, e.g., via binary translation or in another manner, to thus provide emulated instructions to the pipeline to enable their execution within a non-supported core.

Coupled between front end units 210 and execution units 220 is an out-of-order (OOO) engine 215 that may be used to receive the micro-instructions and prepare them for execution. More specifically OOO engine 215 may include various buffers to re-order micro-instruction flow and allo-

cate various resources needed for execution, as well as to provide renaming of logical registers onto storage locations within various register files such as register file 230 and extended register file 235. Register file 230 may include separate register files for integer and floating point operations. Extended register file 235 may provide storage for vector-sized units, e.g., 256 or 512 bits per register.

Various resources may be present in execution units 220, including, for example, various integer, floating point, and single instruction multiple data (SIMD) logic units, among other specialized hardware. For example, such execution units may include one or more arithmetic logic units (ALUs) 222.

When operations are performed on data within the execution units, results may be provided to retirement logic, namely a reorder buffer (ROB) 240. More specifically, ROB 240 may include various arrays and logic to receive information associated with instructions that are executed. This information is then examined by ROB 240 to determine whether the instructions can be validly retired and result data committed to the architectural state of the processor, or whether one or more exceptions occurred that prevent a proper retirement of the instructions. Of course, ROB 240 may handle other operations associated with retirement.

As shown in FIG. 2, ROB 240 is coupled to cache 250 which, in one embodiment may be a low level cache (e.g., an L1 cache) and which may also include TLB 255, although the scope of the present invention is not limited in this regard. From cache 250, data communication may occur with higher level caches, system memory and so forth. Also shown in FIG. 2 is a performance monitoring unit 270, which can monitor execution in the core, e.g., via a set of counters that can be programmably configured to count various events and report results to a variety of locations, including a TCU for purposes of dynamic context switching in accordance with an embodiment of the present invention (not shown in FIG. 2 for ease of illustration).

Note that while the implementation of the processor of FIG. 2 is with regard to an out-of-order machine such as of a so-called x86 ISA architecture, the scope of the present invention is not limited in this regard. That is, other embodiments may be implemented in an in-order processor, a reduced instruction set computing (RISC) processor such as an ARM-based processor, or a processor of another type of ISA that can emulate instructions and operations of a different ISA via an emulation engine and associated logic circuitry. Also understand that the core of FIG. 2 may be a large core, and a lesser number of components, widths, and so forth may be present in the small cores.

Referring now to FIG. 3, shown is a flow diagram of a method in accordance with an embodiment of the present invention. In one embodiment, method 300 may be implemented by logic within a TCU to dynamically control migration of one or more threads between different core types based performance state updates received in the TCU. As seen, method 300 may begin by receiving a P-state update in a power control unit (block 305). For example, a P-state update can be received from the OS, e.g., based on the OS's analysis of code execution. As an example, the P-state update request can be a request to increase the performance state or decrease the performance state from a current level. In turn, the PCU can provide this request to the TCU.

Still referring to FIG. 3, control passes to diamond 310 where it can be determined whether the requested performance state exceeds a threshold performance state. Although the scope of the present invention is not limited in



this regard, in one embodiment this threshold performance state may correspond to a maximum guaranteed operating frequency, e.g., a P1 state. If a higher state is requested, the determination is in the affirmative and accordingly, control passes to diamond **315**.

At diamond **315** it can be determined whether one or more threads within a performance domain are executing on a low power core. This analysis can be done on a per performance domain basis. That is, in some embodiments a processor can be configured to have multiple performance domains such that each domain can operate at an independent performance state (e.g., a different performance state, and corresponding voltage and operating frequency). As an example, an AMP processor can be configured with multiple independent internal voltage regulators to enable operation using per core P-states (PCPS).

If it is determined that the one or more threads of a given performance domain are executing on a low power core, control passes to block **320** where such thread can be migrated to one or more large cores. Otherwise, the method may conclude.

Referring still to FIG. **3**, if the determination at diamond **310** indicates that the requested P-state does not exceed the threshold performance state, control passes to diamond **325** where it can be determined whether one or more threads within this performance domain are executing on large cores. If so, control passes to block **330** where these threads can be migrated to low power cores. In accordance with various embodiments, this context switch can be transparent to the OS. In general operations to perform dynamic migration constitute saving a state of the executing core and providing at least that portion of the state for use in the process to the identified other core type. If these threads are not operating on such large cores as determined at diamond **325**, method **300** may directly conclude. Although shown at this high level in the embodiment of FIG. **3**, understand the scope of the present invention is not limited in this regard. For example migrations may be affected and (possibly limited) by thermal state as described more fully below.

In some embodiments prior to the context switch of threads between different cores, it may also be determined whether a given process has been switched between the cores greater than a threshold number of times. If this count value exceeds a threshold, this indicates that for some reason the process continues to be switched back to the large core from the small core (e.g., for execution of instructions of the code not supported by the small core). The control switch threshold can be changed dynamically based on the system power and performance requirement and the expectation for better or less power/performance efficiency. Accordingly, the overhead incurred in performing the migration may not be worth the effort and thus, a process migration may not occur.

In other embodiments, a task controller may cause dynamic migration between cores based on performance monitor information received in the TCU from one more cores of the processor. Although this dynamic migration control can be based solely on this performance monitor information, in some embodiments combinations of control may occur based on this performance monitor information and P-state information from the OS.

Referring now to FIG. **4**, shown is a flow diagram a method for dynamically migrating threads between cores based on performance monitor information. As seen in FIG. **4**, method **350**, which may be implemented in a TCU of a processor, can begin by analyzing performance monitor information for a workload being executed in a given

performance domain (block **355**). In one embodiment, performance monitoring information can be received from each of multiple performances domains, and can be analyzed on a per domain basis. However, in other implementations performance monitoring information can be received from multiple domains and analyzed globally. Although the scope of the present invention is not limited this regard in some embodiments this performance monitoring information may include information received from performance monitoring units of the multiple cores and may correspond to IPC information, cache statistics, execution performance or so forth.

Referring still to FIG. **4**, at diamond **360** it can be determined whether the performance monitor information exceeds a utilization threshold. As an example, such utilization thresholds can correspond to a given processor utilization value.

If it is determined that the performance monitor information exceeds this utilization threshold, control passes to diamond **370** where it can be determined whether one or more threads of the performance domain are executing on low power cores. If so, control passes to block **375** where the threads can be migrated to large cores. If not, the method may conclude.

Still referring to FIG. **4**, if at diamond **360** it is determined that the performance monitor information does not exceed the utilization threshold, control passes to diamond **380** where it can be determined whether one or more threads of this performance domain are executing on large cores. If so, control passes to block **385**, where the thread can be migrated to a low power core.

On top of the performance metric(s) that can be used by the TCU to decide which type of core is to be used, the TCU is also aware of the current physical constraints like thermal or power budgets that may limit the amount of time that it is possible to use the large core, and to migrate code from the large core to the small core even if the performance metric(s) still justify working on the large core. Also the reverse dynamic change in constraints above may trigger a switch from the small core to the large core during the run time of the executed code.

Note that the operations to dynamically migrate cores based on performance state request updates and/or performance monitoring information can occur in an AMP that includes equal numbers of large and small cores so that if an ISA exception occurs due to a given type of core not supporting a certain instruction, an available core is present to handle a migration due to a fault.

Nevertheless an AMP processor can be implemented without having equal numbers of large and small core pairs. In such embodiments, dynamic migrations may occur when a processor to be operated in a turbo range, namely above a maximum guaranteed operating frequency where the hardware is not obliged to meet an OS performance request; rather it simply tries to honor the request. In such implementations threads that are most likely to gain from switching to a larger, higher power core may be migrated based on the amount of such cores available. It is possible in other implementations that fewer small cores than large cores may be present, with operation generally in the inverse than the described turbo flow.

Referring now to FIG. **5**, shown is a flow diagram of a method for dynamically migrating between cores in the context of an AMP having asymmetric numbers of small and large cores.

In one embodiment, method **400** may be implemented by migration logic within a TCU to dynamically control migra-

tion of one or more threads between different core types and when the numbers of the first and second types of cores (e.g., large and small) are asymmetrical. As with method **300** described above in FIG. **3**, migration may be based on performance state updates received in the TCU. As seen, method **400** may begin by receiving a P-state update in a power control unit (block **405**).

Still referring to FIG. **5**, control passes to diamond **410** where it can be determined whether the requested performance state exceeds a threshold performance state and further whether the requested performance state exceeds a guaranteed performance state. In various embodiments, this guaranteed performance state may correspond to a P0 performance state. Although the scope of the present invention is not limited in this regard, in one embodiment the threshold performance state may correspond to at least one performance bin greater than the guaranteed performance state. If a higher state is requested, the determination is in the affirmative and accordingly, control passes to block **412**. There the number of available (e.g., unused) large cores can be identified. Next control passes to diamond **414**, where it can be determined whether this number N is greater than zero. If not, there are no available large cores, and accordingly a dynamic migration does not occur and thus the method may conclude. Otherwise if N is greater than zero, control passes to diamond **415**.

At diamond **415** it can be determined whether one or more threads within a performance domain are executing on a low power core, which may be done on a per performance domain basis.

If it is determined that the one or more threads of a given performance domain are executing on a low power core, control passes to block **418** where up to N threads having highest performance monitor values greater than a threshold performance state can be identified. In one embodiment, the performance monitor values may correspond to utilization values, although other metrics are equally appropriate, such as instructions per cycle. Control next passes to block **420** where such threads can be migrated to one or more of the available large cores.

Referring still to FIG. **5**, if the determination at diamond **410** indicates that the requested P-state does not exceed the threshold performance state, control passes to diamond **425** where it can be determined whether one or more threads within this performance domain are executing on large cores. If so, control passes to block **430** where these threads can be migrated to low power cores. In accordance with various embodiments, this context switch can be transparent to the OS, as described above. If these threads are not operating on such large cores, method **400** may directly conclude. Although shown at this high level in the embodiment of FIG. **5**, understand the scope of the present invention is not limited in this regard.

Referring now to FIG. **6**, shown is a flow diagram a method for dynamically migrating threads between cores based on performance monitor information for the case of asymmetric numbers of heterogeneous cores. As seen in FIG. **6**, method **450**, which may be implemented in a TCU of a processor, can begin by analyzing performance monitor information for a workload being executed in a given performance domain (block **455**).

Referring still to FIG. **6**, at diamond **460** it can be determined whether the performance monitor information exceeds a utilization threshold and whether the requested performance state exceeds a guaranteed (e.g., P0) performance state. If it is determined that the performance monitor information exceeds this utilization threshold and a higher

than guaranteed performance state is requested, control passes to block **462** where the number N of unused large cores can be identified. Control next passes to diamond **464** where it can be determined whether this number N is greater than zero. If not, no dynamic migration is possible and thus the method may conclude.

Otherwise, control passes to diamond **470** where it can be determined whether one or more threads of the performance domain are executing on low power cores. If so, control passes to block **472**, where up to N threads having the highest performance monitor values over a threshold performance state can be identified. Then control passes to block **475** where these threads can be migrated to large cores. If not, the method may conclude. Still referring to FIG. **6**, if at diamond **460** it is determined that the performance monitor information does not exceed the utilization threshold, control passes to diamond **480** where it can be determined whether one or more threads of this performance domain are executing on large cores. If so, control passes to block **485**, where the thread can be migrated to a low power core.

Referring now to FIG. **7**, shown is a block diagram of a processor in accordance with another embodiment of the present invention. As shown in FIG. **7**, processor **600** may be a multicore processor including a first plurality of cores **610<sub>1</sub>-610<sub>n</sub>** that can be exposed to an OS, and a second plurality of cores **610a-x** that are transparent to the OS. In various embodiments, these different groups of cores can be of heterogeneous size, performance, power, and other capabilities, and understand that these transparent cores can be the larger or smaller cores depending on the embodiment.

As seen, the various cores may be coupled via an interconnect **615** to a system agent or uncore **620** that includes various components. As seen, the uncore **620** may include a shared cache **630** which may be a last level cache. In addition, the uncore may include an integrated memory controller **640**, various interfaces **650a-n**, an advanced programmable interrupt controller (APIC) **665**, and a power control unit **660**. Note that the shared cache may or may not be shared between the different core types in various embodiments.

As further seen in FIG. **7**, power control unit **660** can include various logic units and storages. In the embodiment shown, power control unit **660** can include an exception handler **652** that can be configured to receive and handle via hardware exceptions occurring on cores and/or other components that are transparent to an OS. In this way, this handler can respond to interrupts such as invalid opcode exceptions without OS support. In addition, power control unit **660** can include a state storage **654** that can be used to store the architectural state (and micro-architectural state) of large and small cores for purposes of context switches, including maintaining state of a large core that is not transferred to a small core on a context switch. Still further, power control unit **660** can include a task control logic **658** to determine whether a given process should be migrated between heterogeneous core types. Power control logic **660** may further include a P-state logic **656**, which can receive incoming P-state requests from an OS and determine an appropriate operating frequency for all or portions of the processor based on such requests, e.g., taking into account other constraints on the processor such as thermal, power and so forth. P-state logic **656** may provide information regarding these determined P-states to task control logic **658**.

Although shown with this particular logic in the embodiment of FIG. **7**, understand the scope of the present inven-

tion is not limited in this regard. For example, the various logics of power control unit **660** can be implemented in a single logic block in other embodiments.

APIC **665** may receive various interrupts and direct the interrupts as appropriate to a given one or more cores. In some embodiments, to maintain the small cores as hidden to the OS, power control unit **660**, via APIC **665** may dynamically remap incoming interrupts, each of which may include an APIC identifier associated with it, from an APIC ID associated with a large core to an APIC ID associated with a small core. The assumption is that the APIC ID that was allocated for the core type that was visible to the operating system during boot time is migrated between the core types as part of the core type switch.

With further reference to FIG. 7, processor **600** may communicate with a system memory **680**, e.g., via a memory bus. In addition, by interfaces **650**, connection can be made to various off-chip components such as peripheral devices, mass storage and so forth. While shown with this particular implementation in the embodiment of FIG. 7, the scope of the present invention is not limited in this regard. For example, in some embodiments a processor such as shown in FIG. 7 can further include an integrated graphics engine, which may be of a separate graphics domain.

Embodiments may be implemented in many different system types. Referring now to FIG. 8, shown is a block diagram of a system in accordance with an embodiment of the present invention. As shown in FIG. 8, multiprocessor system **700** is a point-to-point interconnect system, and includes a first processor **770** and a second processor **780** coupled via a point-to-point interconnect **750**. As shown in FIG. 8, each of processors **770** and **780** may be multicore processors, including first and second processor cores (i.e., processor cores **774a** and **774b** and processor cores **784a** and **784b**) each of which can be heterogeneous cores, although potentially many more cores may be present in the processors. Each of the processors can include a power control unit and a task control unit or other logic to perform context switches in a transparent manner to an OS, as described herein.

Still referring to FIG. 8, first processor **770** further includes a memory controller hub (MCH) **772** and point-to-point (P-P) interfaces **776** and **778**. Similarly, second processor **780** includes a MCH **782** and P-P interfaces **786** and **788**. As shown in FIG. 8, MCH's **772** and **782** couple the processors to respective memories, namely a memory **732** and a memory **734**, which may be portions of system memory (e.g., DRAM) locally attached to the respective processors. First processor **770** and second processor **780** may be coupled to a chipset **790** via P-P interconnects **752** and **754**, respectively. As shown in FIG. 8, chipset **790** includes P-P interfaces **794** and **798**.

Furthermore, chipset **790** includes an interface **792** to couple chipset **790** with a high performance graphics engine **738**, by a P-P interconnect **739**. However, in other embodiments, graphics engine **738** can be internal to one or both of processors **770** and **780**. In turn, chipset **790** may be coupled to a first bus **716** via an interface **796**. As shown in FIG. 8, various input/output (I/O) devices **714** may be coupled to first bus **716**, along with a bus bridge **718** which couples first bus **716** to a second bus **720**. Various devices may be coupled to second bus **720** including, for example, a keyboard/mouse **722**, communication devices **726** and a data storage unit **728** such as a disk drive or other mass storage device which may include code **730**, in one embodiment. Further, an audio I/O **724** may be coupled to second bus **720**. Embodiments can be incorporated into other types of sys-

tems including mobile devices such as a smartphone, tablet computer, Ultrabook™, netbook, or so forth.

In the above embodiments, it is assumed that the heterogeneous cores are of the same ISA or possibly of a reduced set of instructions of the same ISA. For example, with reference back to FIG. 1, it can be assumed that both large cores **125** and small cores **130** may be of an x86 architecture. For example, the large cores **125** may correspond to cores having a micro-architecture of an Intel™ Core™ design and the small cores **130** can be of an Intel™ Atom™ design. However understand the scope of the present invention is not limited in this regard and in other embodiments, an AMP processor can include cores of a different design such as ARM-based cores available from ARM Holdings of Sunnyvale, Calif. For example, the large cores may correspond to a Cortex™ A15 design, while the small cores can be of a Cortex™ A7 design. Or an AMP processor may include MIPS-based cores available from MIPS Technologies of Sunnyvale, Calif. Furthermore, as will be described below, embodiments can mix cores of different vendors/licensors and/or ISAs such as cores according to an x86 ISA and cores according to an ARM-based ISA.

Referring now to FIG. 9, shown is a block diagram of a processor **800** in accordance with another embodiment of the present invention. In one embodiment, processor **800** may correspond to a system-on-a-chip (SoC) that can be implemented using heterogeneous cores of a reduced instruction set computing (RISC) ISA. As an example, these cores can be ARM-based cores having heterogeneous resources. As seen in FIG. 9, processor **800** includes a first processor cluster **810** and a second processor cluster **820**. First processor cluster **810** may include a plurality of large cores **812<sub>0</sub>-812<sub>n</sub>**. As seen, each of these cores may be coupled to a shared cache memory **815**, which in one embodiment may be a level 2 (L2) cache memory. Each of large cores **812** may be of an out-of-order architecture. Second processor cluster **810** may include a plurality of small cores **822<sub>0</sub>-822<sub>m</sub>**. As seen, each of these cores may be coupled to a shared cache memory **825**, which in one embodiment may be a L2 cache memory. Each of small cores **822** may be of an in-order architecture.

First processor cluster **810** and second processor cluster **820** may be coupled via one or more interrupt channels to an interrupt controller **830** that may process interrupts received from the various cores. As seen, interrupt controller **830** may include a task control logic **835** in accordance with an embodiment of the present invention to enable transparent migration of tasks between the different processor clusters. As further seen, each processor cluster can be coupled to an interconnect **840** which in an embodiment can be a cache coherent interconnect that further communicates with an input/output coherent master agent **850**. As seen, interconnect **840** also may communicate off-chip, e.g., to and from a DRAM as well as to provide for communication with other components via a system port. Although shown with this particular implementation in the embodiment of FIG. 9, understand the scope of the present invention is not limited in this regard.

As mentioned above, it is also possible to mix cores of different vendors. For example, x86-based cores can be provided on a single die along with ARM-based cores. And with such an architecture, embodiments provide for dynamic migration of processes between these different types of cores transparently to an OS.

Referring now to FIG. 10, shown is a block diagram of a processor in accordance with another embodiment of the present invention. As shown in FIG. 10, processor **900** can

be a multicore processor that includes a core unit **920** having heterogeneous resources. Specifically in the embodiment of FIG. **1**, different types of hardware or physical cores can be present, including a plurality of large cores **925<sub>0</sub>-925<sub>n</sub>** (generically large core **925**), and a plurality of small cores **930<sub>0</sub>-930<sub>m</sub>** (generically small core **930**) (note that different numbers of large and small cores may be present). In the embodiment of FIG. **10**, different micro-architectures are present, including large cores **925** that may be of an x86 architecture and small cores **930** that may be of an ARM, MIPS or other architecture. As examples, the large cores may be of an Intel™ Core™ design and the small cores may be of an ARM Cortex™ design. However, in other embodiments the large cores may be ARM-based and the small cores may be x86-based.

As further seen in FIG. **10**, processor **910** further includes an uncore unit **944** having a power controller or PCU **940**. PCU **940** may receive requests to change P-state of a core. In turn responsive to this request, the PCU can communicate a performance state with a TCU **942**. As further seen, TCU **942** may further receive additional information such as performance monitoring information from performance monitors **926<sub>0</sub>-926<sub>n</sub>** and **936<sub>0</sub>-936<sub>m</sub>** of the cores. TCU **942** can trigger an asynchronous interrupt to enable an OS transparent migration between different core types based on this information.

FIG. **10** also shows the presence of APIC **945** that may receive various incoming interrupts, both from the OS as well as hardware-based interrupts and map such interrupts to a requested core. Furthermore, in accordance with an embodiment of the present invention, dynamic remapping can occur based on control from TCU **942** such that the TCU can dynamically migrate threads between the asymmetric cores transparently to the OS.

Embodiments thus hide physical heterogeneity from the OS and enable taking advantage of heterogeneity without the need for OS support.

The following examples pertain to further embodiments. In one aspect, a multicore processor includes first and second cores to independently execute instructions, where the first core is visible to an OS and the second core is transparent to the OS and heterogeneous from the first core. The processor may further include a task controller coupled to the first and second cores to dynamically migrate a first process scheduled by the OS to the first core to the second core, where this dynamic migration is transparent to the OS. The task controller can dynamically migrate the first process based at least in part on a performance state request received in a power controller from the OS, and can dynamically migrate the first process further based on performance monitor information obtained during execution of the first process on the first core.

In one aspect, the first core is of a first ISA, and the second core is of a second ISA, and where the second core includes an emulation engine to emulate an instruction of the first ISA that is not included in the second ISA. Multiple first cores and second cores may be included, where a number of the first cores is asymmetric to a number of the second cores. A first performance domain may include at least one of the first cores, and the task controller is to dynamically migrate the first process from the first core to the second core based at least in part on a performance state request received in a power controller from the OS corresponding to the first performance domain, and to thereafter dynamically migrate the first process from the second core to the first core based on performance monitor information obtained during execution of the first process on the second core.

The task controller can dynamically migrate N processes each from one of the second cores to one of the first cores, when there are at least N unutilized cores of the plurality of first cores. The N processes may be of X processes executing on the second cores, where X is greater than N and the N processes each have a higher utilization value than the remaining X-N processes.

An exception handling unit can handle an exception occurring during execution of the process on the second core transparently to the OS. The task controller may include a first counter to count a number of times the first process has been switched between the first and second cores, and prevent migration of the first process from the first core to the second core when a value of the first counter is greater than a first threshold.

Another aspect includes a method for receiving a performance state update from an OS in a task controller of a multicore processor including a first plurality of cores and a second plurality of cores, the first plurality of cores visible to the OS and the second plurality of cores transparent to the OS and heterogeneous from the first plurality of cores. The performance state update can request at least one of the first plurality of cores to operate at a requested performance state. Then it can be determined whether the requested performance state exceeds a guaranteed performance state and a threshold performance state and if so, transparently to the OS, at least one thread is migrated from at least one of the second plurality of cores to at least one of the first plurality of cores, where the OS allocated the at least one thread to one of the first plurality of cores.

In addition, it can be determined whether the at least one thread has switched between the first and second plurality of cores greater than a threshold number of times and if so, the at least one thread can be maintained on the first plurality of cores. N unused ones of the first plurality of cores and up to N threads executing on the second plurality of cores with highest performance monitor values over a threshold performance monitor value can be identified, and the N threads can be migrated from the second plurality of cores to the first plurality of cores, while at least one thread is not migrated from the second plurality of cores to the first plurality of cores while migrating the N threads.

Another aspect includes a system with a multicore processor including a first plurality of cores and a second plurality of cores executing in a plurality of performance domains, where the second plurality of cores heterogeneous to the first plurality of cores and transparent to an OS. A power controller can receive a performance state update from the OS for a first performance domain of the plurality of performance domains and performance monitor information from the first and second plurality of cores and cause a context switch to dynamically migrate a process from execution on a second core of the second plurality of cores to a first core of the first plurality of cores transparently to the OS, based on the performance state update and the performance monitor information. A dynamic random access memory (DRAM) may be coupled to the multicore processor. The second core can include an emulation logic to emulate an instruction of a first ISA, where the second core of a different ISA than the first ISA. A number of the first plurality of cores may be different than a number of the second plurality of cores.

Embodiments may be used in many different types of systems. For example, in one embodiment a communication device can be arranged to perform the various methods and techniques described herein. Of course, the scope of the present invention is not limited to a communication device,

and instead other embodiments can be directed to other types of apparatus for processing instructions, or one or more machine readable media including instructions that in response to being executed on a computing device, cause the device to carry out one or more of the methods and techniques described herein.

Embodiments may be implemented in code and may be stored on a non-transitory storage medium having stored thereon instructions which can be used to program a system to perform the instructions. The storage medium may include, but is not limited to, any type of disk including floppy disks, optical disks, solid state drives (SSDs), compact disk read-only memories (CD-ROMs), compact disk rewritables (CD-RWs), and magneto-optical disks, semiconductor devices such as read-only memories (ROMs), random access memories (RAMs) such as dynamic random access memories (DRAMs), static random access memories (SRAMs), erasable programmable read-only memories (EPROMs), flash memories, electrically erasable programmable read-only memories (EEPROMs), magnetic or optical cards, or any other type of media suitable for storing electronic instructions.

While the present invention has been described with respect to a limited number of embodiments, those skilled in the art will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover all such modifications and variations as fall within the true spirit and scope of this present invention.

What is claimed is:

1. A multicore processor comprising:

a first core to execute instructions independently from other cores;

a second core to execute instructions independently from other cores, the first core visible to an operating system (OS) adapted for a symmetric processor and the second core transparent to the OS and heterogeneous from the first core, the multicore processor comprising an asymmetric processor;

a hardware task controller coupled to the first and second cores to dynamically migrate a first process, scheduled by the OS to a first virtual core associated with the first core via an allocation of the first process to the first core based on a mapping table having an association between a first identifier sent from the OS to the first core, to the second core, where the dynamic migration is transparent to the OS; and

a hardware power controller coupled to the hardware task controller and the first and second cores and to receive a performance state request for the first core from the OS and communicate the performance state request to the hardware task controller, wherein the hardware task controller is to dynamically migrate the first process based at least in part on the performance state request for the first core received in the hardware task controller from the hardware power controller and performance monitor information received in the hardware task controller from the first core during execution of the first process on the first core, via an update to the mapping table to associate the first identifier with the second core, wherein the hardware task controller is to prevent the dynamic migration of the first process to the second core when a number of switches of the first process between the first core and the second core exceeds a threshold number of switches and enable the dynamic migration of the first process when the number of switches is less than the threshold number of switches.

2. The multicore processor of claim 1, wherein the first core is of a first instruction set architecture (ISA), and the second core is of a second ISA.

3. The multicore processor of claim 2, wherein the second core includes an emulation engine to emulate an instruction of the first ISA that is not included in the second ISA.

4. The multicore processor of claim 1, further comprising a plurality of first cores including the first core and a plurality of second cores including the second core, wherein a number of the plurality of first cores is asymmetric to a number of the plurality of second cores.

5. The multicore processor of claim 4, further comprising a first performance domain including at least one of the plurality of first cores, wherein the hardware task controller is to dynamically migrate the first process from the first core to the second core based at least in part on a performance state request received in the hardware power controller from the OS corresponding to the first performance domain.

6. The multicore processor of claim 5, wherein the hardware task controller is to thereafter dynamically migrate the first process from the second core to the first core based on performance monitor information obtained during execution of the first process on the second core.

7. The multicore processor of claim 4, wherein the hardware task controller is to dynamically migrate N processes each from one of the plurality of second cores to one of the plurality of first cores, when there are at least N unutilized cores of the plurality of first cores.

8. The multicore processor of claim 7, wherein the N processes are of a plurality of X processes in execution on the plurality of second cores, X greater than N and wherein the N processes each have a higher utilization value than the remaining X-N processes.

9. The multicore processor of claim 1, further comprising an exception handling unit to handle an exception occurring during execution of the first process on the second core transparently to the OS.

10. The multicore processor of claim 1, wherein the second core is of a different instruction set architecture (ISA) than the first core, and the different ISA is partially overlapping with an ISA of the first core.

11. The multicore processor of claim 1, wherein the hardware task controller is to dynamically migrate the first process further based on a detection that the performance state request exceeds a guaranteed performance state and a threshold performance state.

12. The multicore processor of claim 11, wherein the threshold performance state exceeds the guaranteed performance state by at least one performance bin.

13. A method comprising:

receiving a performance state update from an operating system (OS) in a controller of a multicore processor including a first plurality of cores and a second plurality of cores, the first plurality of cores visible to the OS and the second plurality of cores transparent to the OS and heterogeneous from the first plurality of cores, wherein the performance state update requests at least one of the first plurality of cores to operate at a requested performance state;

determining that the requested performance state exceeds a guaranteed performance state and a threshold performance state exceeding the guaranteed performance state, the threshold performance state at least one performance state greater than the guaranteed performance state;

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maintaining a count of a number of switches of at least one thread between the first plurality of cores and the second plurality of cores;  
 responsive to determining that the requested performance state exceeds the guaranteed performance state and the threshold performance state, migrating, transparently to the OS, the at least one thread from at least one of the second plurality of cores to at least one of the first plurality of cores, wherein the OS allocated the at least one thread to one of the first plurality of cores, when the count of the number of switches of the at least one thread between the first plurality of cores and the second plurality of cores is not greater than a threshold number of times; and  
 maintaining the at least one thread on the second plurality of cores responsive to determining that the count of the number of switches of the at least one thread between the first plurality of cores and the second plurality of cores is greater than the threshold number of times.

**14.** The method of claim **13**, further comprising identifying N unused ones of the first plurality of cores and identifying up to N threads executing on the second plurality of cores with highest performance monitor values over a threshold performance monitor value.

**15.** The method of claim **14**, further comprising migrating the N threads from the second plurality of cores to the first plurality of cores.

**16.** The method of claim **13**, wherein the second plurality of cores is of a different instruction set architecture (ISA) than the first plurality of cores, and the different ISA is partially overlapping with an ISA of the first plurality of cores.

**17.** A system comprising:

a multicore processor including a first plurality of cores and a second plurality of cores to execute in a plurality of performance domains, the second plurality of cores

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heterogeneous to the first plurality of cores and transparent to an operating system (OS), and a power controller, wherein the power controller is to receive a performance state update from the OS for a first performance domain of the plurality of performance domains and performance monitor information from the first and second plurality of cores and to cause a context switch to dynamically migrate a process from execution on a second core of the second plurality of cores to a first core of the first plurality of cores transparently to the OS, based on the performance state update and the performance monitor information, wherein the second plurality of cores is of a different instruction set architecture (ISA) than the first plurality of cores, and the different ISA is partially overlapping with an ISA of the first plurality of cores and the power controller includes a counter to count a number of switches of the process between the first and second cores, wherein the power controller is to prevent the dynamic migration of the process between the first core and the second core when the number of switches exceeds a threshold number of switches and enable the dynamic migration of the process when the number of switches is less than the threshold number of switches; and  
 a dynamic random access memory (DRAM) coupled to the multicore processor.

**18.** The system of claim **17**, wherein the second core includes an emulation logic to emulate an instruction of a first instruction set architecture (ISA), the second core of a different ISA than the first ISA.

**19.** The system of claim **17**, wherein a number of the first plurality of cores is different than a number of the second plurality of cores.

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